

8.2(II) Drag of the Complete Configuration Aerodynamic Considerations

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Introduction

The purpose of this part of the paper is to focus on a number of drag items and relate them to the performance of the complete configuration.

First, the effect of fuselage camber, wing and nacelle incidence are discussed from a viewpoint of design decision making.

Second, the effect of overall cruise drag on the design gross and empty weight of the airplane is discussed. Examples show that cruise drag can have a very important influence on total airplane weight.

Third, the effects of usable cruise lift-to-drag ratio and wing-loading are shown to be important.

Finally several research needs relating to design of the complete configuration are reviewed.

Effect of Fuselage Camber, Wing and Nacelle Incidence

In putting together a new airplane, a number of fundamental geometric choices must be made. Typical examples of such choices are:

- extent of fuselage camber;
- wing incidence on fuselage; and
- nacelle incidence and position relative to the wing.

In determining the extent of wind tunnel testing required to "optimize" the configuration, the aerodynamicist is confronted with a large number of variables. For example, if it is assumed, that two camber shapes, two wing-fuselage incidence angles and two wing-nacelle incidence angles are to be investigated, this alone leads to eight combinations to be tested. Under the economic constraints of the general aviation industry it is usually not feasible to do this much testing.

Major aircraft manufacturers, on fighter, bomber and even on some transport programs, obtain significant inputs from NASA in terms of systematic wind tunnel configuration testing.

How does the general aviation designer choose the best configuration? Well, very often he ends up guessing or, the shaping decision (for lack of definitive aerodynamic input) is made for him by engineers or managers outside of aerodynamics.

Inputs such as tooling costs and marketing opinions outweigh the aerodynamicist in the decision making process, primarily because the aerodynamicist does not have convincing arguments one way or the other.

To illustrate these points and to point once more to the need for systematic tunnel testing of general aviation research models, the following examples are given.

Note from Figure 1 that three different vertical nacelle installations are being used for turbopropeller airplanes. Note also, that all three use rather differing aft fairing shapes. The question arises: can they all be right?

Observe from Figure 2 that one manufacturer employs two quite different piston engine nacelle configurations. Figure 3 illustrates two more and again different nacelle shapes. The questions arises again: can they all be right?

Possible pay-offs of such research are illustrated in Figure 4 taken from Reference 1 (1942). Figure 4 shows a range of wing-body-nacelle drag coefficients of .1250 to .1050, (.0078 to .0066 based on wing area!) depending on vertical nacelle location alone. In other words, there are 12 drag counts to be gained by selecting the vertical nacelle location.

It would seem that the industry could derive significant benefits from a series of systematic wind tunnel test to determine the best (lowest drag) shape of such wing-nacelle installations. Such research should also account for the effect of thrustline location and orientation, as well as for the possible beneficial effect of forward propeller shaft extensions, such as used on the Navajo.

Drag Effect on Airplane Weight and Airplane Market Price

Aerodynamic drag is not generally thought of in general aviation airplane design as an important factor affecting airplane weight. The reason may be the fact that usually new airplane "designs" consist of adaptations of components which are already in production, to a new airplane. The term "tinker toying", although not a kind description probably applies to much of general aviation airplane design.

However, every now and then a truly new design evolves and then the effect of drag on weight can be important as will be illustrated in the following simplified analysis.

Assume that total airplane weight is broken down as follows:

$$W = W_{PL} + W_F + W_E \quad (1)$$

where:

W_{PL} = payload weight

W_F = fuel weight (including reserves)

W_E = empty weight

Fuel weight and empty weight are assumed to be broken down as follows:

$$W_F = \bar{A} + T \times \text{SFC} \times \frac{V}{R} \quad \text{and:} \quad (2)$$

$$W_E = \bar{B} + \bar{C}T + \bar{D}W_F \quad (3)$$

where:

\bar{A} = weight of reserve fuel

T = cruise thrust

SFC = cruise fuel consumption lbs/lbs/hr

V = cruise speed

R = cruise range

\bar{B} = empty weight without power plant and fuel system

\bar{C} = weight of power plant per lbs of cruise thrust

\bar{D} = weight of fuel system per lbs of cruise fuel

In cruise flight:

$$T = W \text{ and } L = D \quad (4)$$

lift drag

so that

$$T = W \left(\frac{D}{L} \right) \quad (5)$$

Substituting equations (2) through (5) into equation (1) yields:

$$W = W_{PL} + \left(\bar{A} + W \frac{D}{L} (\text{SFC}) \frac{V}{R} \right) + \left(\bar{B} + \bar{C} W \frac{D}{L} \right) + \bar{D} \left(\bar{A} + W \frac{D}{L} (\text{SFC}) \frac{V}{R} \right) \quad (6)$$

Upon solving for W it is found that:

$$W = \frac{W_{PL} + \bar{A} + \bar{B} + \bar{D}\bar{A}}{1 - \frac{D}{L} \left\{ (\text{SFC}) \frac{V}{R} + \bar{C} + \bar{D}(\text{SFC}) \frac{V}{R} \right\}} \quad (7)$$

or

$$W = \frac{W_{PL} + \bar{A}(1 + \bar{D}) + \bar{B}}{1 - \frac{D}{L} \left\{ (\text{SFC}) \frac{V}{R} (1 + \bar{D}) + \bar{C} \right\}} \quad (7)$$

By introducing:

$$a = W_{pL} + \bar{A}(1 + \bar{D}) + \bar{B} \quad (8)$$

$$b = (\text{SFC}) \frac{V}{R} (1 + \bar{D}) + \bar{C} \quad (9)$$

it is possible to rewrite equation (7) as:

$$W = \frac{a}{1 - b/L/D}$$

To determine the effect of drag on airplane weight, the differential $\partial W / \partial (L/D)$ can be found from equation (10) as:

$$\frac{\partial W}{\partial (L/D)} = \frac{-ab}{(L/D - b)^2} \quad (11)$$

Table 1 presents data from which $\partial W / \partial (L/D)$ can be calculated for a typical general aviation piston engine driven twin.

So using equation (11):

$$\frac{\partial W}{\partial L/D} = \frac{-4326 \times 2.15}{(11 - 2.15)^2} = -119 \text{ lbs}/(L/D)$$

This means that per unit L/D, the airplane gross weight can be lowered by about 120 lbs, a significant saving when compared to the empty weight, W_E .

Figures 5 and 6 illustrate similar results obtained in Reference 2 on small two-place turboprop (1200 lbs max thrust) airplanes.

Table 1 and Figure 5 and 6 all show the importance of designing to the maximum possible cruise lift-to-drag ratio, if the lowest possible airplane weight is to be achieved.

It should be noted, that lower empty weight, achieved by better aerodynamic design has a very significant effect on the marketing price of an airplane. Table 2 shows typical market prices related to gross and empty weights for general aviation twins.

For the example twin of Table 1 the typical market price per pound of empty weight would be about 34 \$/lbs. Attaining a 120 lbs saving would cut the market price by \$4,080, a rather significant competitive advantage!

Table 2. Typical General Aviation Light Twin Airframe Prices,
(1975 Flying Annual Data)

| Type | Gross Weight W (lbs) | Empty Weight W _E (lbs) | Price \$ | Price $\frac{Price}{W}$ \$/lbs | Price $\frac{Price}{W_E}$ \$/lbs |
|------------------------------|-------------------------|--------------------------------------|-------------|--------------------------------------|--|
| Cessna Skymaster | 4,630 | 2,710 | 63,300 | 13.7 | 23.4 |
| Piper Seneca | 4,570 | 2,770 | 63,995 | 14.0 | 23.1 |
| Piper Aztec E | 5,200 | 3,042 | 88,200 | 17.0 | 29.0 |
| Beech Baron B55 | 5,100 | 3,155 | 89,000 | 17.5 | 28.2 |
| Cessna 310 | 5,500 | 3,251 | 89,950 | 16.4 | 27.7 |
| Averages | 5,000 | 2,986 | 78,889 | 15.7 | 26.3 |
| Rockwell Shrike Commander | 6,750 | 4,608 | 128,150 | 19.0 | 27.8 |
| Cessna 402 B | 6,300 | 3,741 | 138,500 | 22.0 | 37.0 |
| Piper Navajo B | 6,500 | 3,930 | 139,100 | 21.4 | 35.4 |
| Cessna 414 | 6,350 | 4,042 | 174,950 | 27.6 | 43.3 |
| Beech Duke | 6,775 | 4,265 | 219,450 | 32.4 | 51.5 |
| Averages | 6,535 | 4,117 | 160,030 | 24.5 | 39.0 |

the left in the higher C_L range (note that C_{D_0} actually will increase because it is based on a smaller wing area!). This fact has been previously demonstrated also in such papers as References 3, 4, and 5.

Figure 8 illustrates some typical results. Cutting wing area in the chordwise direction by 30 percent results in a 10 percent reduction in thrust required and therefore in fuel flow. Figure 9, shows the relative aerodynamic "cleanness" of 1975 general aviation single engine airplanes compared to what is felt feasible in the future. To achieve this however, will require the introduction of new designs and new manufacturing technology.

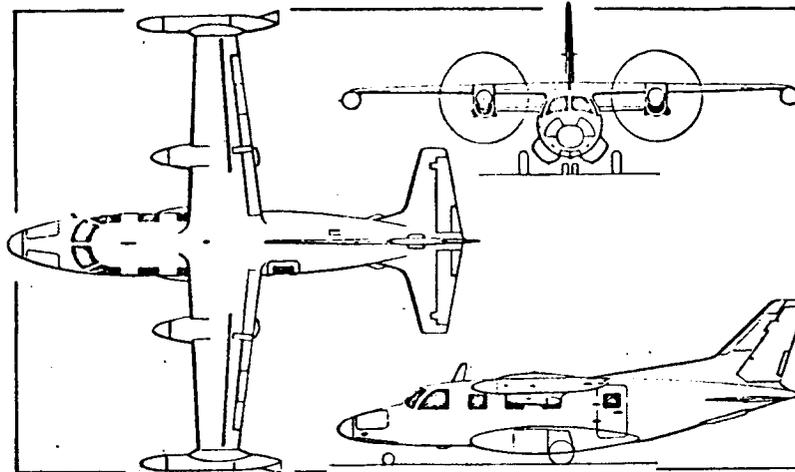
Research Needs

It appears that research into the following areas would have significant potential for paying off in improved general aviation airplanes:

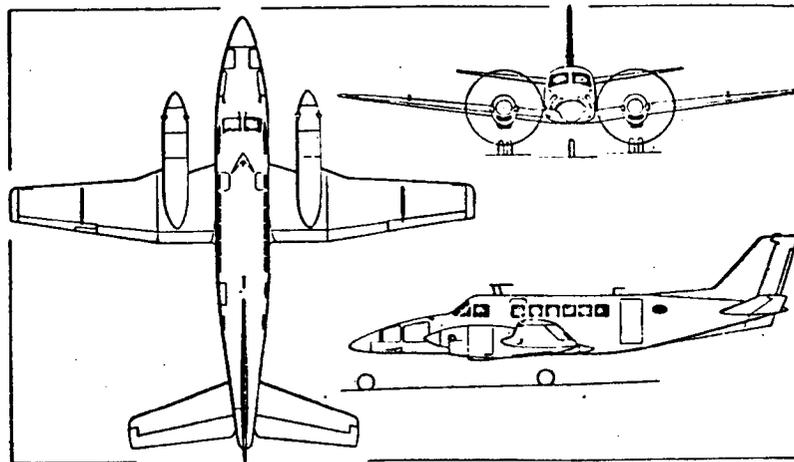
- Nacelle shape and nacelle location on wings (for horizontally opposed piston engines and for turbo propeller installation);
- Improved methods for predicting the effect of drag on weight (Adaptation of NASA/Ames GASP?); and
- Expansion and specialization of GASP to single engine and twin engine propeller driven airplanes with detailed accounting for weight, stability and control and propulsion interference factors.

References

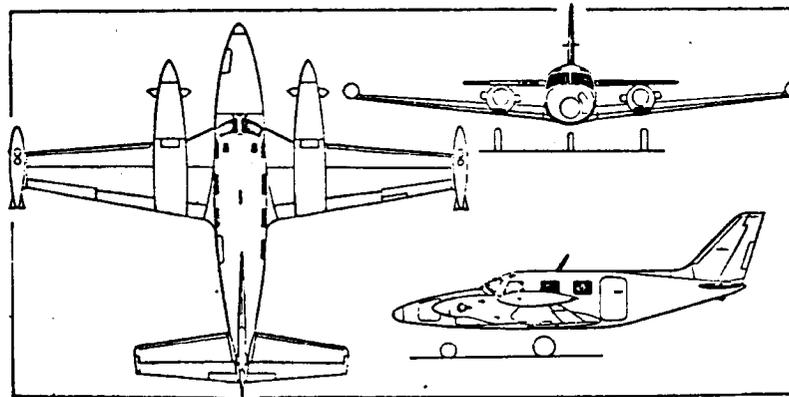
1. Becker, G.V. and Leonard, L.H.; High Speed Tests of a Model Twin-Engine Low-Wing Transport Airplane; NACA TR 750, 1942.
2. Heldenbrand, R.W.; Merrill, G.L. and Burnett, G.A.; Study of Small Civil Turbofan Engines Applicable to Military Trainer Airplanes: Final Report; NASA CR 137575; Garrett Airesearch 74-210987-A; April 1975.
3. Roskam, J.; Opportunities for Progress in General Aviation Technology; AIAA Paper 75-292, Presented at the AIAA 11th Annual Meeting and Technical Display, Washington, D.C. February 24-26, 1975.
4. Roskam, J.; New Airfoils and Higher Wing Loadings: A New Look at General Aviation Airplane Design; Paper presented at the Technological University of Delft, The Netherlands, May 20, 1974.
5. Roskam, J. and Kohlman, D.L.; An Assessment of Performancy, Stability and Control Improvements for General Aviation Aircraft; SAE Paper 700240 presented at the SAE Business Aircraft Meeting, Wichita, Kansas, April 1970.



Mitsubishi MU-2G twin-turboprop utility transport

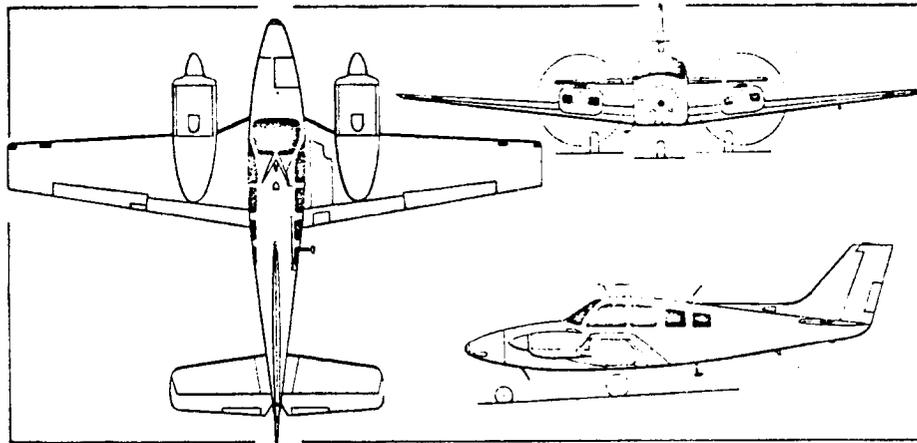


Beechcraft 99 Airliner seventeen-seat light transport

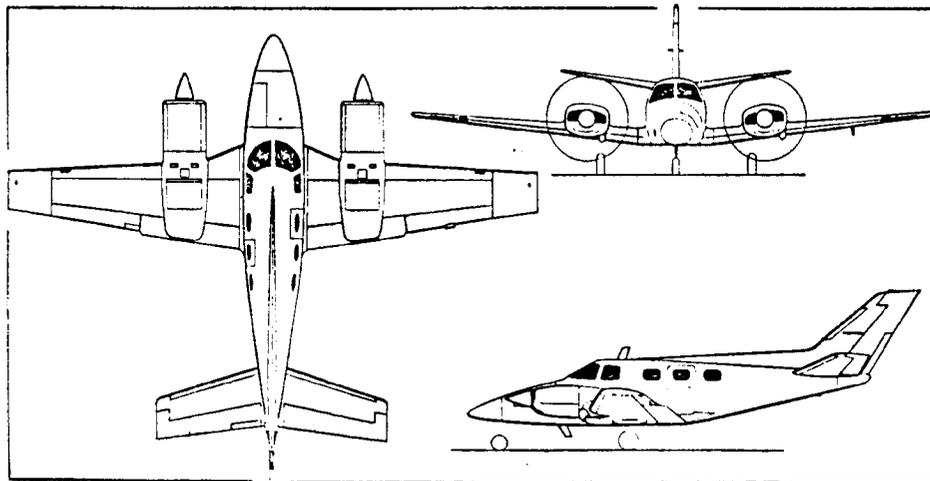


Piper PA-31T Cheyenne six/eight-seat light transport aircraft (Pilot Press)

Figure 1. Examples of General Aviation Turbopropeller Installations

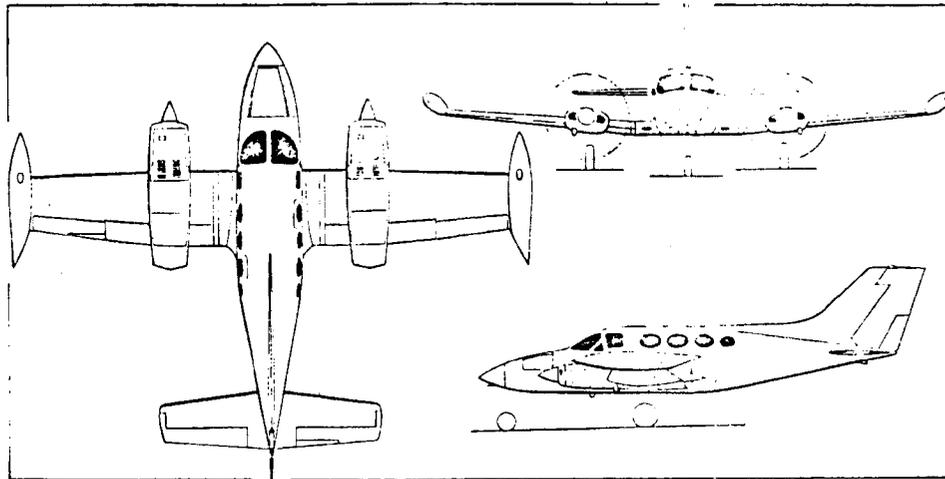


Three-view drawing of the Beechcraft Baron 58 four/six-seat cabin monoplane

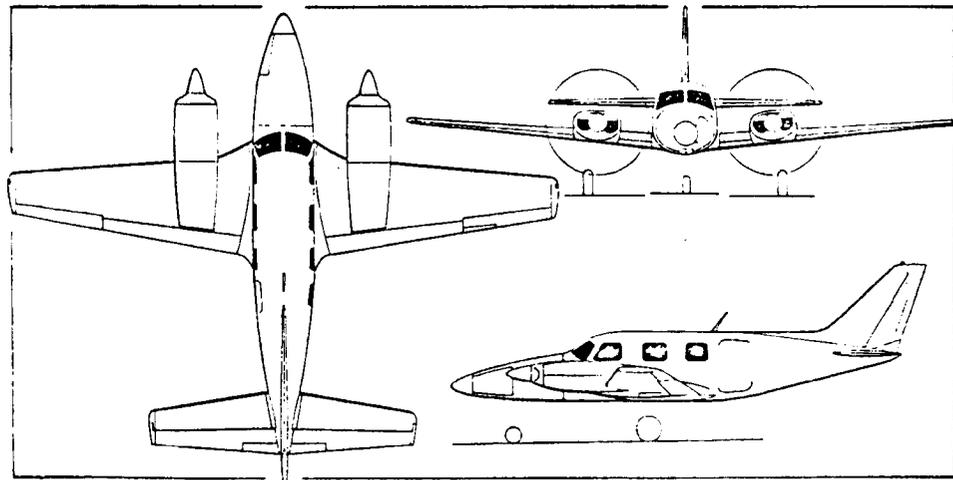


Three-view drawing of the Beechcraft Duke B60 4/6-seat pressurized transport (two 380 hp Lycoming T10-541-E1C4 engines)

Figure 2. Different Piston Engine Nacelle Shapes Used by One Manufacturer



Cessna Model 414 pressurised light transport



Three-view drawing of the Piper PA-31P Pressurised Navajo
(two 425 hp Lycoming T1GO-541-E1A engines)

Figure 3. Further Examples of Piston Engine Nacelle Shapes

(REF. 1)

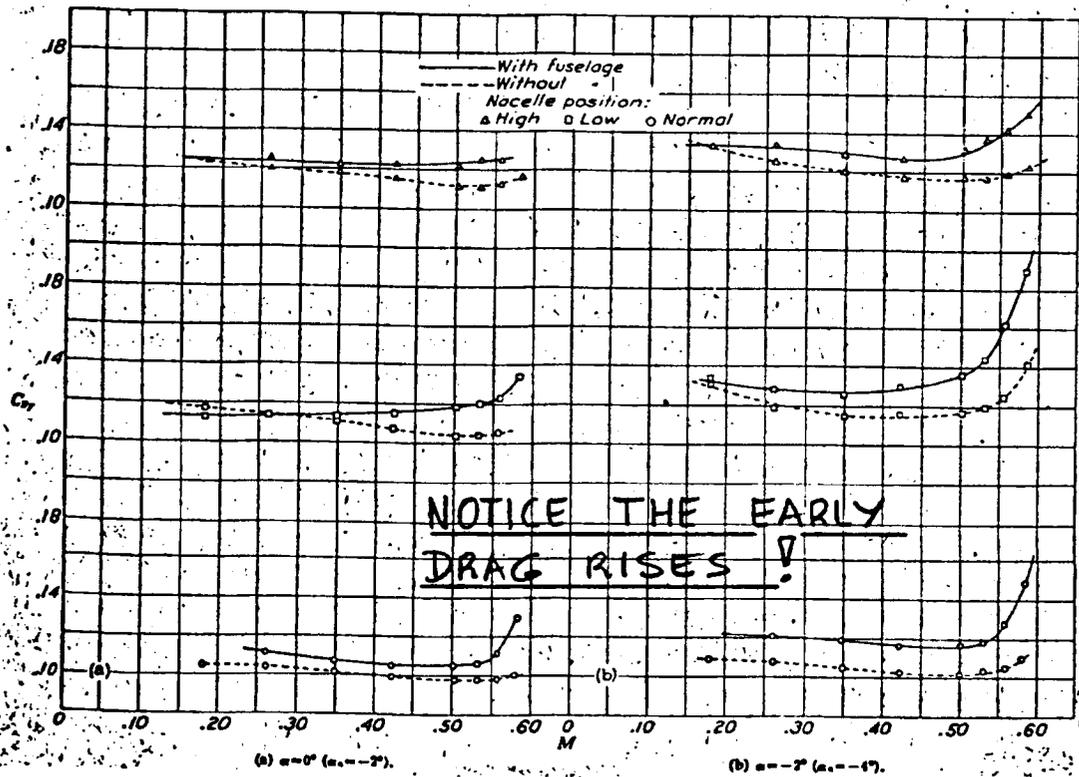
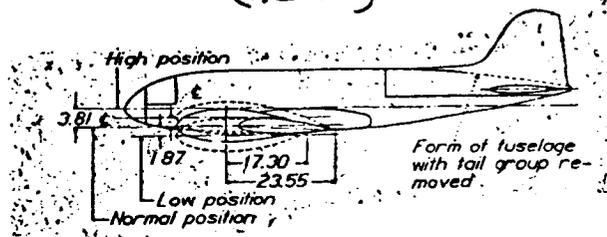


Figure 4. Example of the Effect of Vertical Nacelle Location on Drag

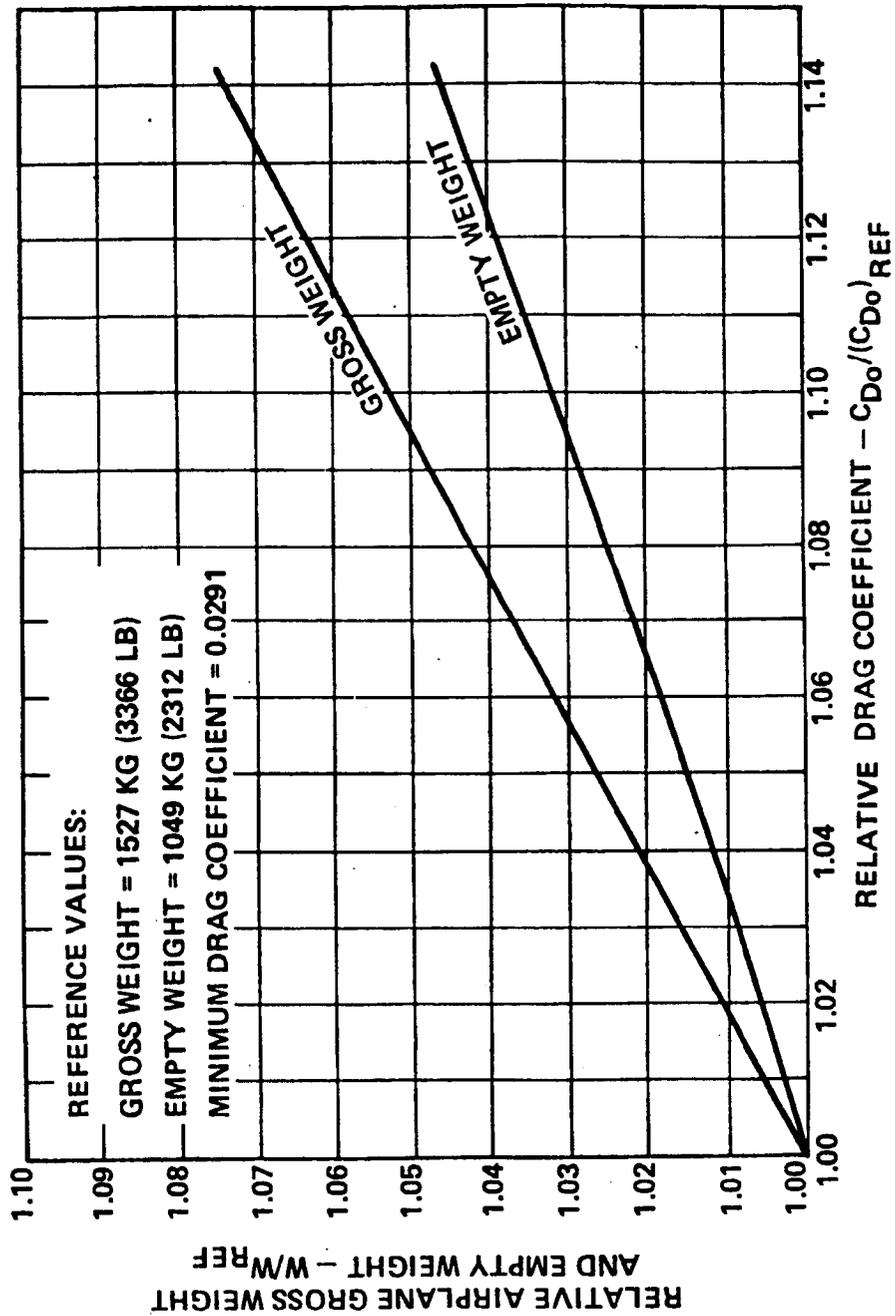


Figure 5. Gross and Empty Weight Sensitivity to Zero-Lift Drag Coefficient

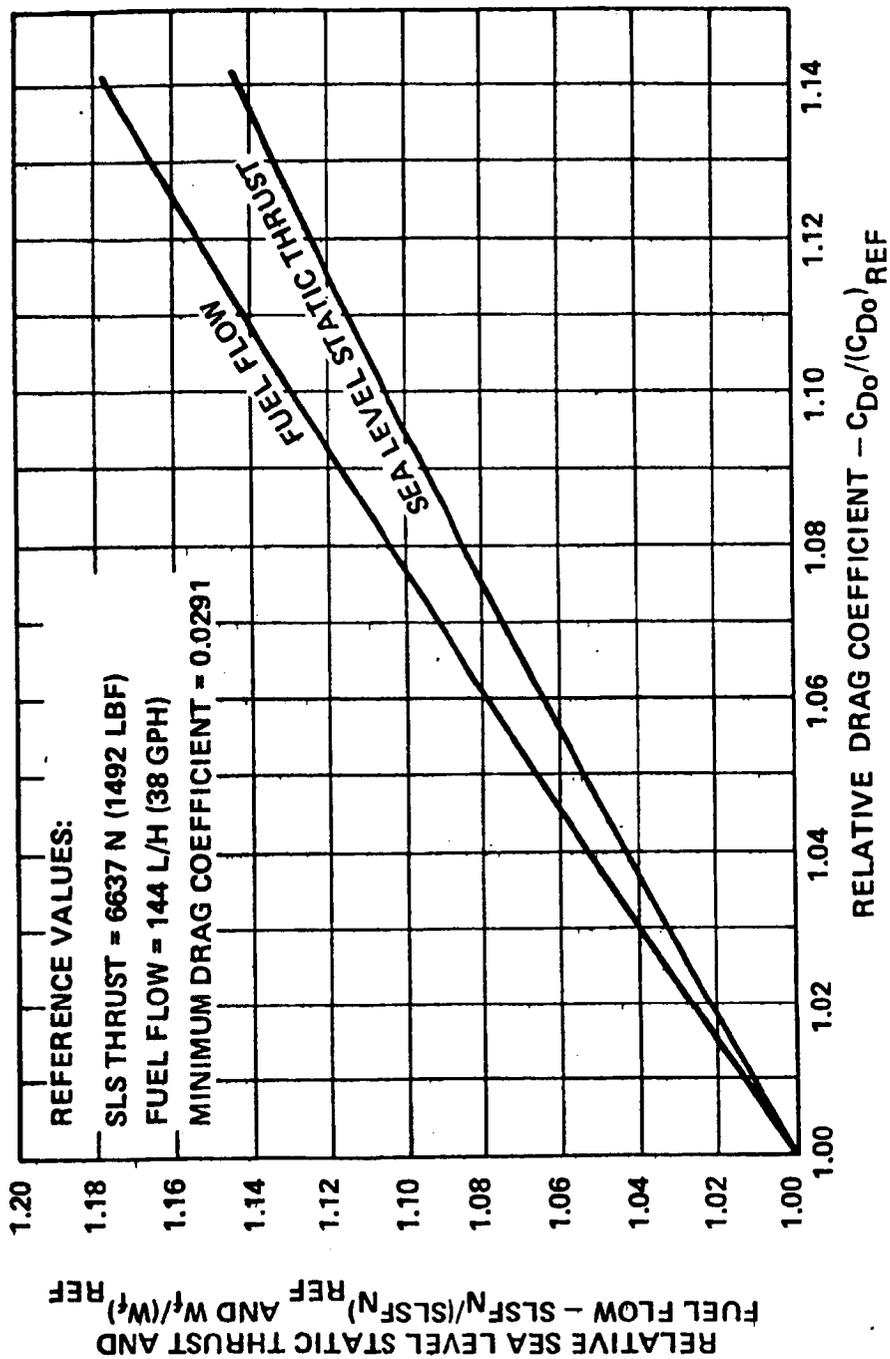


Figure 6. Engine Size and Cruise Fuel Consumption Sensitivity to Zero-Lift Drag Coefficient

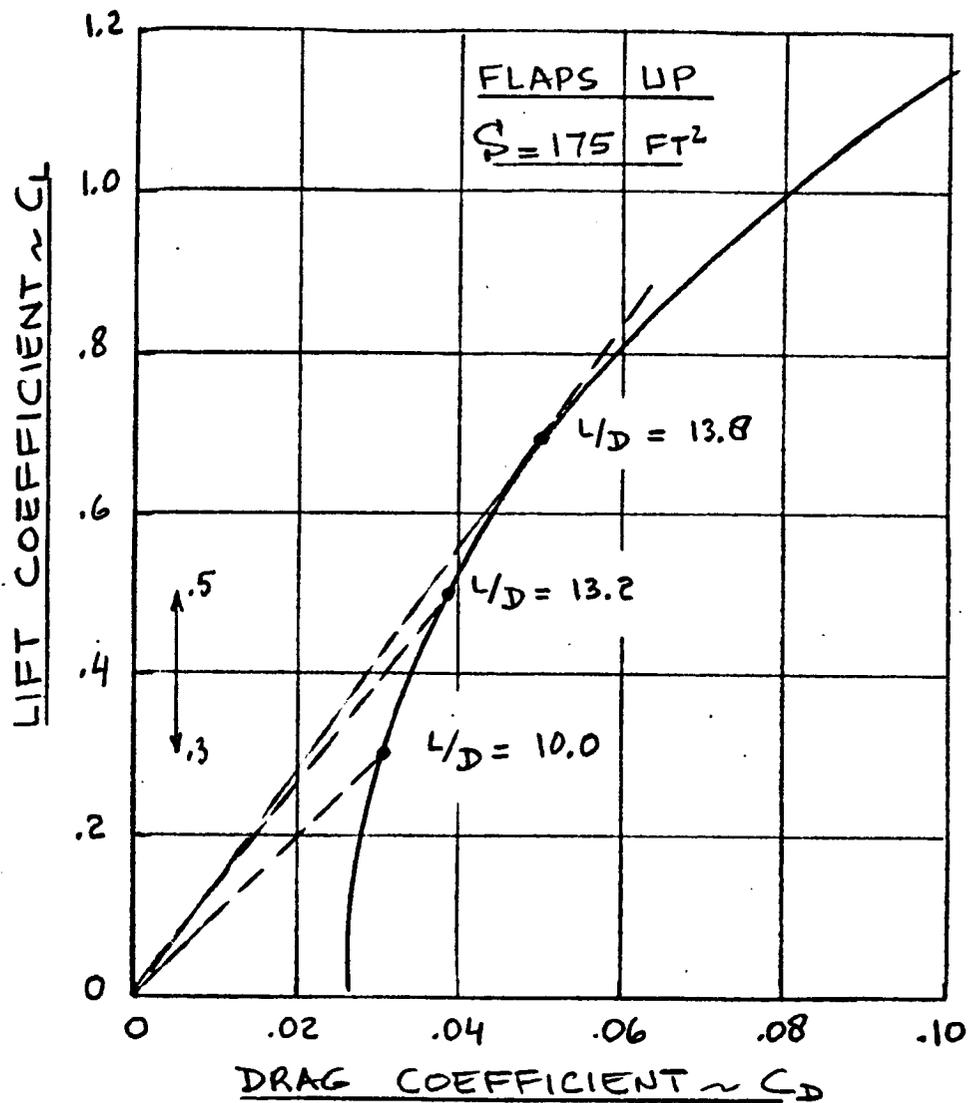


Figure 7. Typical Single Engine Airplane Drag Polar

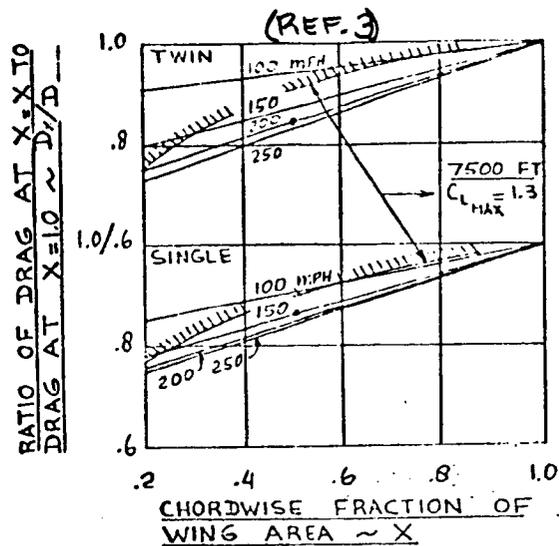


Figure 8. Effect of Chordwise Area Reductions on Thrust Required

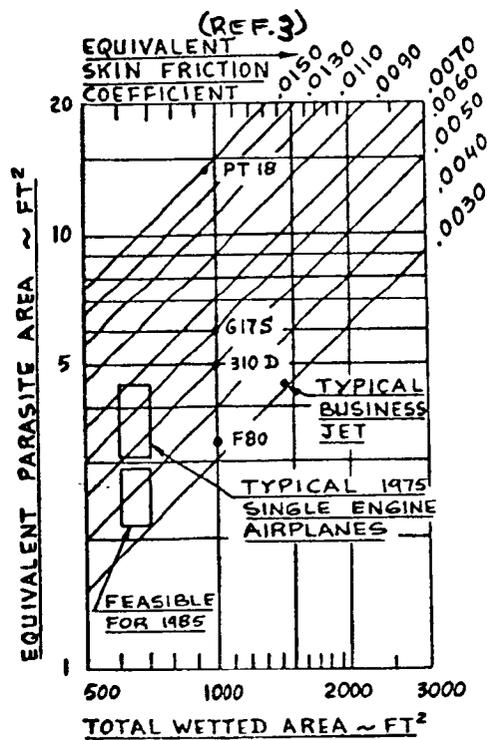


Figure 9. Typical Range of Wetted Areas and Equivalent Parasite Drag for General Aviation Airplanes